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Risk Analysis of Natural Gas Distribution Pipelines with Respect to Third Party Damage

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Abstract

The objective of this study is to develop a quantitative method of evaluating the risk of third party damage (TPD) on natural gas distribution pipelines using available industry data and practical engineering experience. A risk model for TPD of gas distribution pipelines is developed to allow for a more robust decision making process and better prioritization of the allocation of resources for operators of natural gas distribution pipelines. The model consists of likelihood and consequence classification procedures to estimate the severity of TPD events within an area.

The TPD model consists of a fault tree (FTA) model to estimate the probability of hit of a given distribution pipeline by third party excavation activities. The distribution FTA model is developed using TPD and locate records from 2014-2016 and survey data from transmission FTA models. This model is then validated by comparing the predicted and actual 2017 damage records in three municipalities in southwestern Ontario with populations varying from 200,000 to 350,000.

Based on a historical analysis of distribution pipeline TPD consequence, a procedure is developed to classify the consequence of a TPD event within a given area. Methods of collecting and classifying data from sources available to distribution companies are used to allow this procedure to be implemented straightforwardly in an industry setting. In a case study a compromise solution method of evaluation is used to identify areas where focusing damage prevention resource would be most effective.

Keywords

Natural Gas, Distribution Pipelines, Fault Tree Analysis, Risk Analysis, Third Party Damage

Co-Authorship Statement

The author acknowledge Professor Wenxing Zhou from the University of Western Ontario for guidance and assistance in the review process and Carrie Dudley-Tatsu of Union Gas Ltd for assistance in data collection in Chapter 2, Third-Party Damage Models for Gas Distribution Pipelines, published at the ASME Proceedings of the 12th International Pipeline Conference.

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1 Introduction

1.1 Background

Natural gas is commonly transported by a series of pipeline systems from the site of extraction to use by the consumer. Distribution pipelines are the final step in the delivery of natural gas to the end users (e.g. residential homes and industrial sites). Distribution pipeline networks are generally fed from long distance, large-diameter, high–pressure transmission pipelines, typically with a 3450 to 6160 kPa maximum operating pressure (MOP) which are fed by gathering lines from production wells. They are typically linear systems with few connections [1]. Distribution systems are usually interconnected networks where gas can be received from various sources in branch or tree configurations [1]. This allows for a portion of the system to be taken offline for repair while minimizing the number of customers affected. Back feeding these distribution systems is especially important in natural gas distribution because loss of service requires pilot lights to be relit for every affected customer, which can be costly [2].

In Southwestern Ontario, Canada, most of the distribution systems operates at 420 kPa MOP, with 80% of distribution main consisting of NPS2 or smaller pipes, a majority of which are made of polyethylene plastic (PE). Third-party damage (TPD), damage caused by work unrelated to the pipeline operation, is a leading cause of failure for gas distribution systems [3]. An analysis of the US Pipeline and Hazardous Material Safety Administration (PHMSA) data since 1984 shows that TPD accounted for over 50% of incidents on distribution pipelines. Analyses of reported TPD in the continental United States and five Canadian provinces (Quebec, Ontario, Saskatchewan, Alberta, and British Columbia) in 2016 showed that of 91,539 reported incidents, 99.6% occurred on distribution and service lines [4].

The Common Ground Alliance (CGA), founded in 2001[4], is a non-profit organization that established best practices for the underground utility industry (natural gas, electricity, telecommunications, etc.) which are now reviewed and implemented through CGA organizations in Canada and the United States. These CGA organizations, like the

Ontario Regional Common Ground Alliance (ORCGA) provide best practices regarding TPD prevention after pipe installation. Most TPD damage is a failure of these best practices and is broken down by root cause:

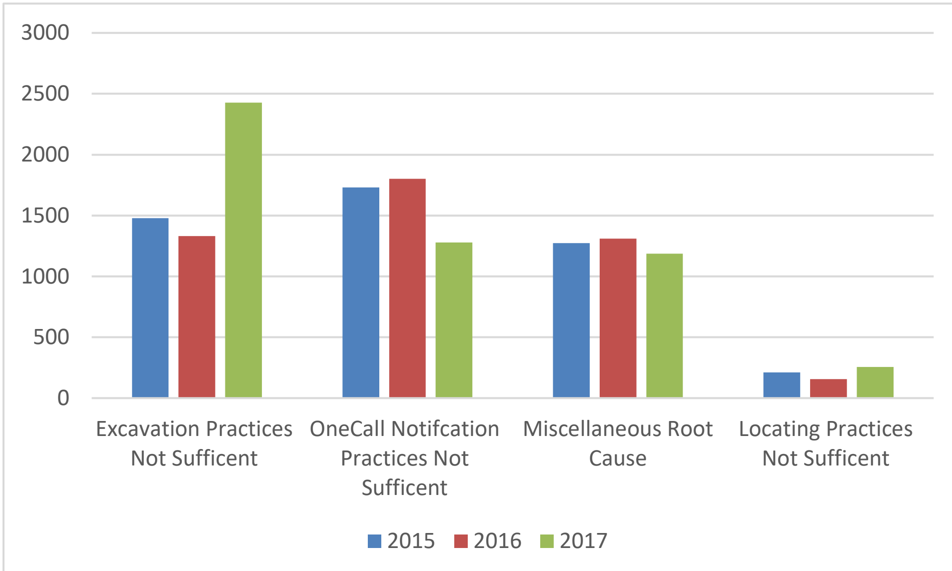

Figure 1.1 2015-2017 TPD Incidents in Ontario by Root Cause

The ORCGA publishes the Damage Information Reporting Tool (DIRT) report annually which outlines the major causes of TPD and prevention information in Ontario. This report breaks down the last three years of TPD data for all utility types, with 47% of all incidents in the 2015-2017 period being attributed to natural gas pipelines. In 2017 the Toronto area saw a 30% increase in TPD events, which may explain the significant increase in 2017 excavation practices not sufficient category. This data includes 19,973,512 locate requests and 14,441 TPD incidents over the three year period.

Figure 1.1 indicates that the two most likely contributing factors to TPD are a failure of excavation best practices or a failure to notify OneCall. The miscellaneous root cause category includes deterioration of facility, previous damage, OneCall center error, or root cause not listed. 89% of all miscellaneous category reports in 2017 were caused by missing data. Locating practices not sufficient refers to errors in facility records, maps, and errors in the marking of facility locations. In Ontario, there were 2,741 incidents on natural gas distribution lines and connected services that led to customer disruptions in

2016 [4]. One major utility company in Ontario currently has over 65,000 km of in-service distribution pipelines, for which TPD is a leading cause of pipeline damages.

1.2 Objective

The objective of this project is to provide a quantitative method of evaluating the risk of third-party damage (TPD) on natural gas distribution pipelines and to develop a practical tool to identify third-party damage hot spots, develop proactive third-party damage prevention measures, and prioritize damage repair activities using a risk-based approach. TPD is any activity not related to the pipeline, such as residential construction, that causes damage to the distribution pipeline. Distribution assets are the last stage of the natural gas delivery process and generally range from NPS1¼ to NPS16 diameter and usually operate at maximum operating pressure (MOP) between 2.5 -1900 kPa. For the purpose of this analysis risk is defined as the likelihood of an event occurring and the consequence of that event should it occur.

1.3 Scope and Format

This thesis is presented in an Integrated- Article Format thesis as specified by the School of Graduate and Postdoctoral Studies at the University of Western Ontario, London ON, Canada. Chapter 1 gives a brief introduction of the background, objective and scope of the study. The main body of the thesis includes Chapters 2, 3, which is presented in an integrated-article format without an abstract, but with its own references. Chapter 4 presents the summary and conclusions of this thesis, and recommendations for future study. A quantitative method of evaluating risk is focused on providing a method for defining risk through available industry data and practical engineering experience. Publicly available data was combined with Ontario distribution gas utility records and developed in conjunction with industry experts in an attempt to formulate techniques that are both practical and useful for engineers in industry.

Chapter 2 will outline the procedure for evaluating the likelihood of a TPD event occurring on a distribution pipeline using a fault tree analysis, published at the International Pipeline Conference 2018, and includes a validation of the model using predictions of TPD incident frequency in three cities. Chapter 3 will outline a procedure to evaluate the consequence of those events based on pipeline attributes classified by an analysis of the TPD events. These two procedures will then be combined into a risk model and shown in a case study which evaluates the risk in a city and presents it in a GIS environment to aid in the presentation and decision making of distribution utility TPD mitigation efforts. Recommendations will be presented based on a compromise programing analysis of the indices developed by this model.

1.4 References

[1] Mike Musial, Glenn DeWolf, Doug Orr, Julie Martin, and Pilar Odland. “Safety Performance and Integrity of the Natural Gas Distribution Infrastructure.” URS Corporation, Chicago, IL. 2005.

[2] Canadian Common Ground Alliance. “National Report on Damage to Underground Infrastructure”. Damage Prevention Symposium 2015. http://www.canadiancga.com/resources/Documents/2015%20DIRT%20Committee%20Documents/2015.DIRTReport.pdf

[3] Julie K. Maupin. “Plastic Pipe Failure Analysis”. Proceedings of IPC2008. IPC2008-64355.

[4] Common Ground Alliance. “Damages Reported by State- Ontario 2016.” DIRT 2016 - Interactive Report. http://commongroundalliance.com/dirt-2016-interactive-report

2 Fault Tree Analysis of TPD Frequency

2.1 Introduction

2.1.1 Overview of Natural Gas Transmission

Natural gas is commonly transported by a series of pipeline systems from the site of extraction to use by the consumer. Distribution pipelines are the final step in the delivery of natural gas to the end users (e.g. residential homes and industrial sites). As shown in Fig. 2.1, distribution pipeline networks are generally fed from long distance, large-diameter, high–pressure transmission pipelines, typically 3450 to 6160 kPa maximum operating pressure (MOP) which are fed by gathering lines from production wells. They are typically linear systems with few connections [1]. Distribution pipelines are connected to transmission systems by regulator stations that control the pressure of the downstream system [1]; there may be several regulator stations in a given distribution system. Distribution pipelines generally range from NPS1¼ to NPS16 diameter and operate at MOP between 2.5 -1900 kPa.

Distribution systems are usually interconnected networks where gas can be received from various sources in branch or tree configurations [1]. This allows for a section of the system to be isolated in an event of damage, therefore minimizing the number of customers affected. Back feeding these distribution systems is especially important in natural gas distribution because loss of service can have a substantial economic impact on distribution utilities and their customers [2]. Each customer is connected to the distribution main by a service main (considered to be part of the distribution system) and meter, which brings the gas to the building where usage is recorded and reduces the gas pressure before it enters the premises.

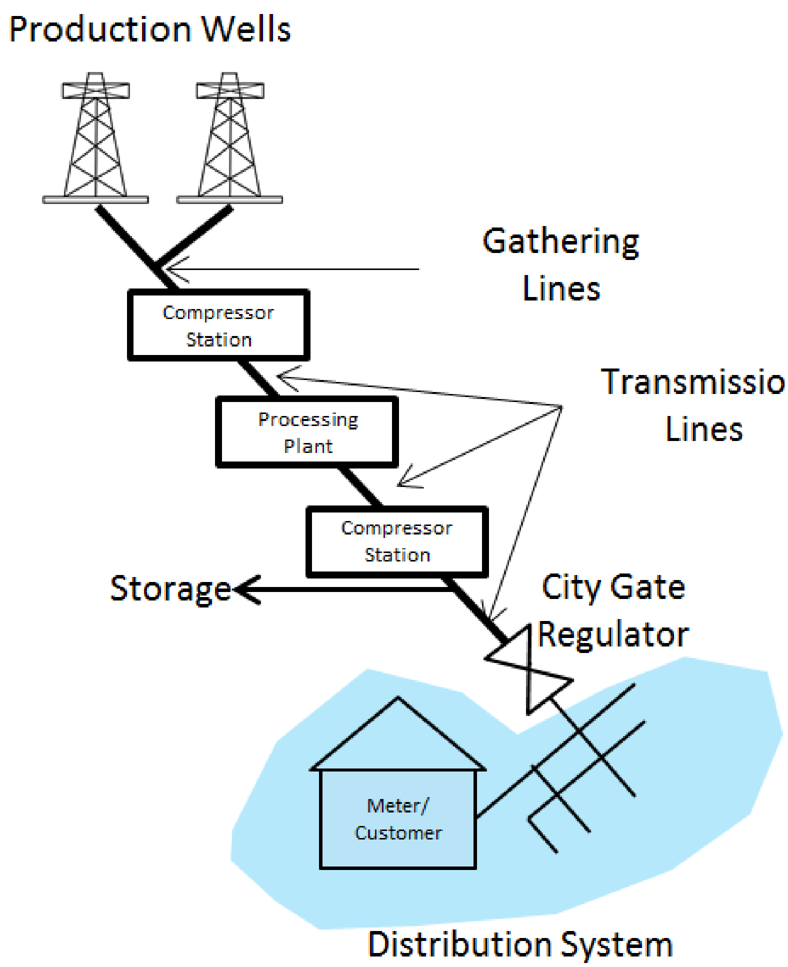

Figure 2.1 Typical Path of Natural Gas from Production to Customer

In Canada and the US, pipelines used in the natural gas industry consist of steel and polyethylene (PE) pipes. PE pipes account for a significant portion of the gas distribution systems with MOP less than 550 kPa and pipe diameters smaller than or equal to NPS4. In the US, the proportion of PE pipes in the gas distribution system increased from 35 to 51% from 1995 to 2006 [3]. In Southwestern Ontario, Canada, most of the distribution systems operates at 420 kPa MOP, with 80% of distribution main consisting of NPS2 or smaller pipes, a majority of which are made of PE.

Third-party damage (TPD) is a leading cause of failure for gas distribution systems [3]. An analysis of the US Pipeline and Hazardous Material Safety Administration (PHMSA) data since 1984 shows that TPD accounted for over 50% of all incidents causing damage to distribution pipelines. Analyses of reported TPD in the continental United States and five Canadian provinces (Quebec, Ontario, Saskatchewan, Alberta, and British Columbia) in 2016 showed that of 91,539 reported incidents, 373 occurred on transmission and gathering lines, with the remaining on distribution and service lines [4]. In Ontario, there were 2,741 incidents on natural gas distribution lines and connected services that led to customer disruptions in 2016 [4]. One major utility company in Ontario currently has over 65,000 km of in-service distribution pipelines, for which TPD is a leading cause of pipeline damages.

2.1.2 Common Ground Study and Third Party Damage Prevention

The Common Ground Alliance (CGA), founded in 2001[4], is a non-profit organization that is the direct result of the Common Ground Study sponsored by the United States Department of Transportation Office of Pipeline Safety, as authorized by the Transportation Equity Act for the 21st Century (TEA 21)[5]. It established best practices for the underground utility industry (natural gas, electricity, telecommunications, etc.) which are now reviewed and implemented through CGA organizations in Canada and the United States. These CGA organizations, like the Ontario Regional Common Ground Alliance (ORCGA) provide best practices regarding TPD prevention after pipe installation and can be broken down into the following process:

1. Contractor/resident calls Ontario OneCall or submits a form providing dig information at least 5 business days before dig is to take place.

2. OneCall takes collected utility data and compares known locations of underground infrastructure to specified area in request.

3. If area contains underground infrastructure, a utility service representative (USR) will come to the worksite and locate infrastructure using an electromagnetic tool and mark the lines using some combination of flags and spray paint. These marks are color coated by type of utility, for example natural gas lines will be marked using yellow.

4. During construction the area within 1m of these marks are hand dug, to avoid accidental damage.

Most TPD damage is a failure of one of these steps to occur properly.

2.2 Review of TPD Models for Transmission Pipelines

The reliability based approach has been used to quantify the likelihood of TPD on transmission pipelines [1,2]. This was accomplished by using a fault tree model to estimate the probability of a pipeline being hit by third-party excavation activities, and a puncture resistance model to determine the probability of failure given hit. The process of developing a fault tree model is commonly completed by starting at the top level event of interest, in this case a pipeline being hit during excavation, and breaking down that event into the necessary inputs required for that event to occur. This process is then repeated on each event in the subsequent level of the fault tree until all base level events can be characterized using relevant available data. The main variables contributing to a puncture include the wall thickness, equipment bucket tooth size, and yield strength.

However, the TPD model for the transmission pipelines is not applicable to distribution pipelines due to the differences in the characteristics of the pipe attributes and typical preventative measures employed for these two types of pipeline systems. Many of the base events used in the transmission pipeline fault tree model are not applicable to distribution pipelines, a full list of which can be found in Appendix 2A. As far as the authors of this paper are aware, the quantification of the TPD likelihood for distribution systems has not been reported in the literature. The objective of this research is to develop a model that is suited for qualifying the likelihood of TPD for distribution pipelines and facilitate risk-based integrity management of distribution pipelines with respect to TPD.

The fault tree analysis (FTA) is a top down, deductive failure analysis method that uses Boolean logic to combine a series of basic events to analyze the state of a system. This model uses a series of AND and OR relationship gates to combine independent probabilities using Eq. (1) and Eq. (2), respectively:

$$P_{and} = P_1 \bullet P_2 \ldots \bullet P_n \tag{2.1}$$

$$P_{or} = 1 - [(1 - P_1) \bullet (1 - P_2) \bullet \ldots (1 - P_n)] \tag{2.2}$$

where P_{and} and P_{or} are the probabilities of the AND and OR gates, respectively, and P_1, P_2, …, P_n are the probabilities of n basic events combined using the AND/OR gates.

Prior research demonstrated the ability of FTA to quantify the probability of natural gas transmission pipelines being hit by third party excavation activities [5,6]. These models allow for a quantitative analysis of the effectiveness of preventative measures and, in conjunction with current practices, facilitate a predictive method to plan and optimize resource allocation for damage mitigation and emergency preparedness. This modeling technique is applied to natural gas distribution pipeline systems in the present study, and a predictive model is developed and validated based on available industry data.

The base level should include factors that contribute to the top level event, and allow for the collection of data and assumptions made in conjunction with experts to estimate the probability of occurrence. Basic events included in the FTA model for gas transmission pipelines [1] are

- excavation activity rate;
- depth of cover;
- effectiveness of notification practices;
- patrol activities;
- right of way (ROW) recognition;
- permanent and temporary markers;
- malicious intent, and
- physical resistance to damage.

The probabilities of basic events are estimated based on the results of an industry-wide survey. The FTA model in Ref [1] was combined with a puncture resistance model that quantifies the impact force of the excavator as a function of its weight and the puncture resistance of the pipeline as a function of its wall thickness, yield strength, and excavator's bucket tooth size. Probability distributions of the impact force and puncture resistance, respectively, are then developed. The probability of puncture is then the probability of the impact force of the excavator exceeding puncture resistance of the pipeline.

2.3 TPD Model for Distribution Pipelines

2.3.1 FTA Model for Probability of Hit

The FTA model for transmission pipelines described in the previous section is used as a starting point in the construction of a TPD model for distribution pipelines. The initial development process of each event in the transmission pipeline fault tree model is evaluated for its applicability to distribution systems. Input from engineers in a major distribution pipeline operator in Ontario is used to justify the elimination of variables that do not play a significant role in distribution systems. These include:

- patrol frequency;
- use of buried or permanent markers, and
- right of way signage.

Malicious intents towards pipelines, such as gas being siphoned illegally or deliberate damage, are also excluded due to a lack of evidence that this is a prevalent issue in Canada. Variables influenced by factors such as the OneCall process and awareness, excavation activity rate around pipelines, and failures involving preventative measures are included as these processes are common to all natural gas pipelines. The Damage Information Reporting Tool (DIRT) report [3] separates the cases of third-party damage in Ontario by root cause and sub-category. This allows for the estimation of the basic event probabilities that define the failure of preventative measures section of the distribution fault tree. A full list of considered variables is summarized in Appendix 2A.

A fault tree for evaluating the probability of hit, P_{Hit}, of a distribution pipeline due to a given third-party excavation activity (see Figure 2.2 and Table 2.1) is developed and implemented in the statistical computing language and environment R using the R-forge fault tree library. The FTA assumes that the event of the pipeline being hit by the third-party excavation activity results from a failure of the preventative measures in place to prevent TPD, the excavation activity being in the vicinity of a pipeline, and the excavation depth exceeding the burial depth of the pipeline. Based on the developed fault tree model, P_{Hit} is evaluated as follows:

$$P_{Hit} = P_{PF} \bullet P_{DEC} \bullet P_A \tag{2.3}$$

$$P_{PF} = 1 - [(1 - P_{NL}) \bullet (1 - P_{FoC}) \bullet (1 - P_{IM})] \tag{2.4}$$

$$P_{NL} = P_{NLU} \bullet P_{NLC} \tag{2.5}$$

$$P_{NLU} = 1 - [(1 - P_{NC}) \bullet (1 - P_{DBL})] \tag{2.6}$$

$$P_{NC} = 1 - [(1 - P_{NCN}) \bullet (1 - P_{NCU})] \tag{2.7}$$

where P_{PF} is the probability of failure of all preventative measures; P_{DEC} is the probability of the excavation depth exceeding pipe burial depth, and P_A is the probability that the activity is in the vicinity of pipeline. Note that all basic events involved in the fault tree are assumed to be mutually independent of each other.

The probability of failure of all preventative measures is determined from Eq. (2.4) using the probability of no locates on site (P_{NL}), probability of construction error (P_{FoC}), and probability of temporary markers being placed incorrectly (P_{IM}). The value of P_{NL} is determined from Eq. (2.5) using the probability that an excavator will not use OneCall (P_{NLU}), and probability of the third-party not properly locating the pipeline (P_{NLC}). The value of P_{NLU} is determined from Eq. (2.6) using the probability of digging before locate is completed (i.e. the third party contacts OneCall but fails to wait for the pipeline operator to locate the pipeline before digging) (P_{DBL}) and the probability that OneCall is not contacted (P_{NC}). The value of P_{NC} is determined from Eq. (2.7) using the probability that no call made as a result of unawareness of OneCall (P_{NCU}) and the probability no call made as a result of the third party neglecting OneCall (P_{NCN}). The evaluation of the basic event probabilities are described in detail in later sections.

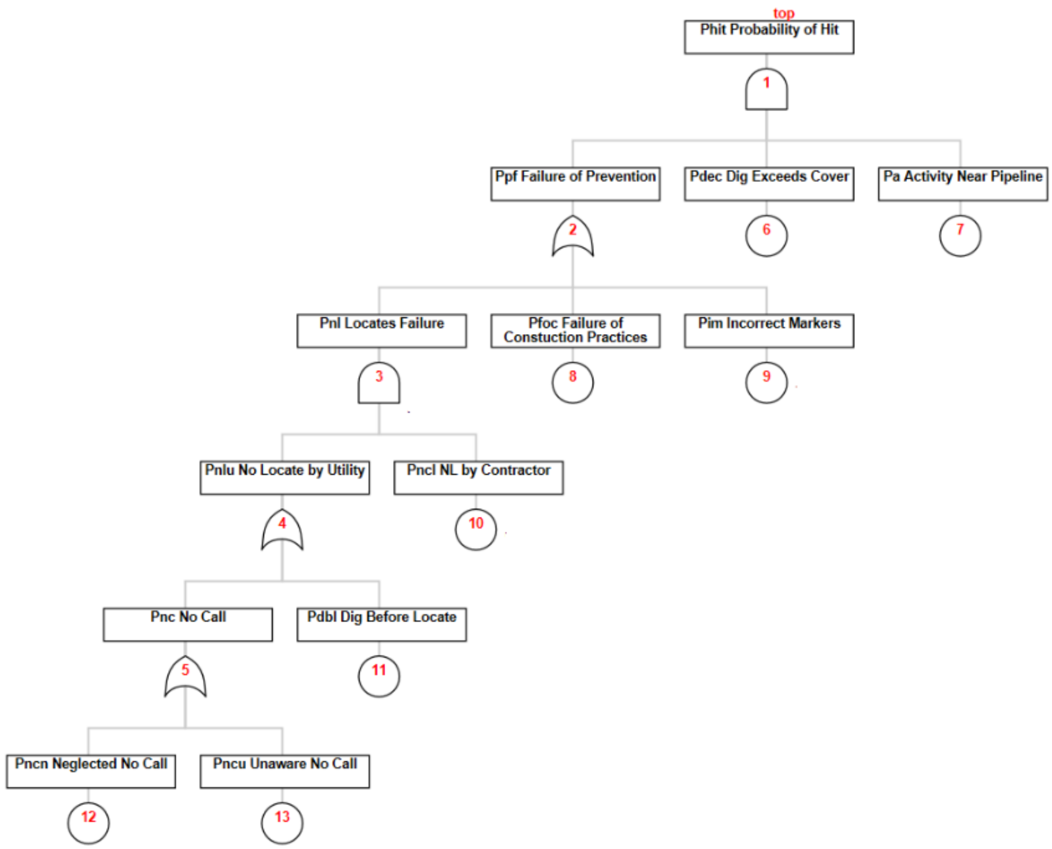

Figure 2.2 TPD Fault Tree Model

2.3.2 Probability of Failure Given Hit

Transmission pipelines have relatively thick walls and high yield strengths that offer resistance if hit. However, distribution pipelines are mostly small diameters and have thin wall thickness. It can therefore be inferred that the puncture resistance of distribution pipelines is much lower than that of transmission pipelines and can be considered negligible. It follows that the probability of failure given hit is assumed to be unity in this study. This is justified by both the pipe incident and attribute data collected from a major distribution pipeline operator in Southwestern Ontario. The incident data collected indicates that 97% of TPD incidents occurred on pipelines smaller than NPS4. Between 2014 and 2016 there were no cases reported where a NPS2 PE pipe was not punctured when hit. The breakdown by pipe diameter of the overall length (approximately 6,134 km) of distribution pipelines owned by the above-referred pipeline operator is shown in Figure 3; as shown in Figure 3, over 80% of distribution pipelines in this system are NPS 2 or less, a vast majority of which are PE pipes.

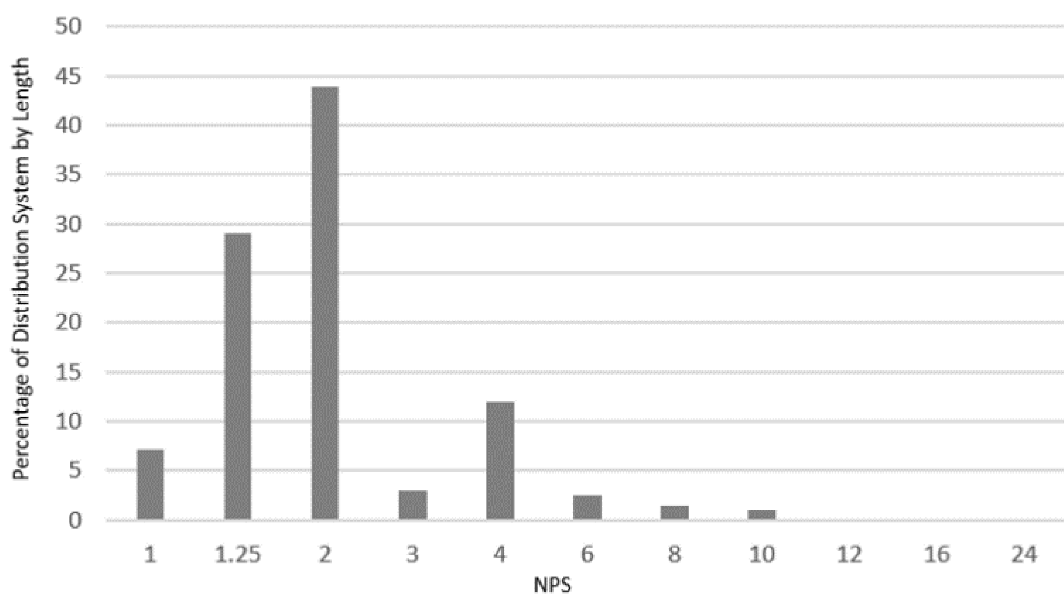

Figure 2.3 Distribution of NPS by Length

2.4 Quantification of Probabilities of Basic Events

2.4.1 Digging Depth Exceeding Depth of Cover

The minimum depth of cover is estimated based on requirements for installations of new distribution pipelines in Ontario. It is assumed that a majority of the in-service distribution pipelines still meet or exceed the minimum cover depth for new installations. In Southwestern Ontario, the minimum depth of cover requirements for non-agricultural, non-rock excavated buried pipelines operated at below 30%-SMYS hoop stresses are 1000 mm for mainlines and 500 mm for service lines. Based on these requirements and input from pipeline engineers, a deterministic depth of cover of 450 mm is conservatively assumed in this study.

The probability distribution of the excavation depth is derived using the estimated maximum excavation depths presented in the locate requests information for Southwestern Ontario between 2014 and 2016. By eliminating unrealistic estimated excavation depths (0 and above 4 m), a total of 43,414 estimated excavation depths have been collected. The corresponding histogram and cumulative distribution function (CDF) of the collected data are shown in Figures 4 and 5 respectively. A lognormal distribution with a mean value of 1.29 m and a standard deviation of 0.86 m is found to be the best-fit distribution for the data. The CDF of this fitted distribution is shown in Figure 5; given that the burial depth is assumed to be a deterministic value of 0.45 m, it follows that the probability of the excavation depth exceeding the burial depth equals 0.80.

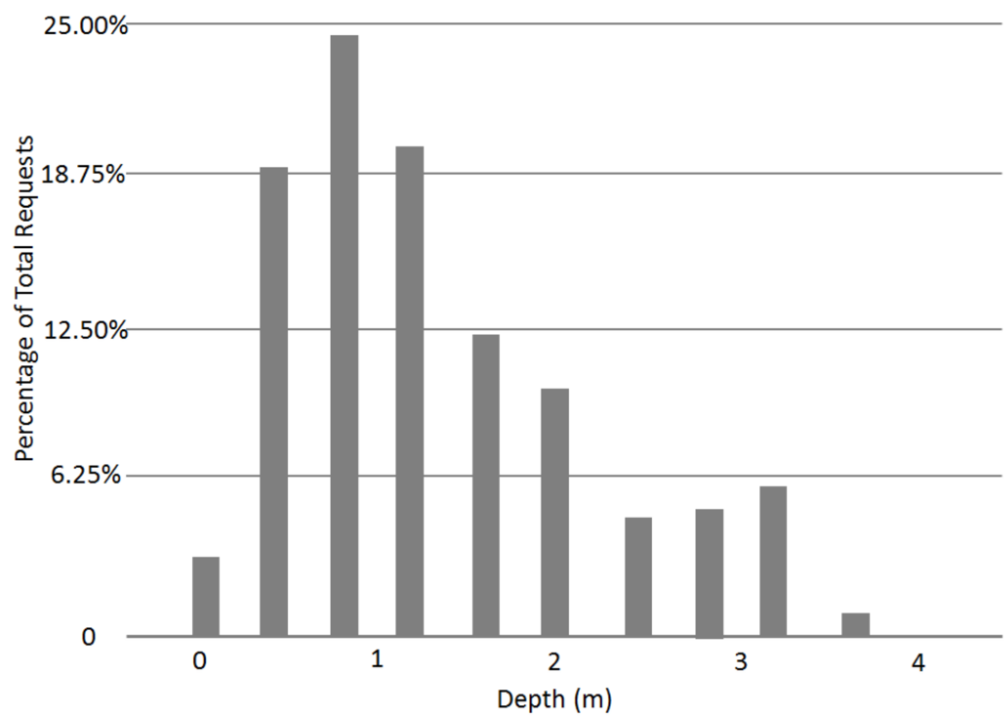

Figure 2.4 Histogram of submitted digging depths in OneCall tickets

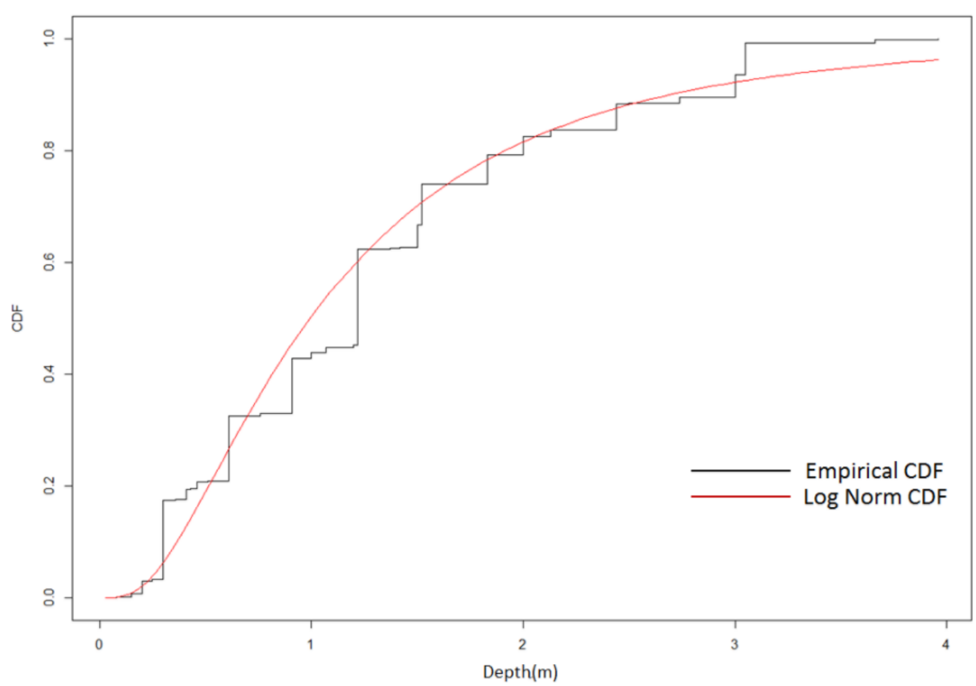

Figure 2.5 Cumulative distribution functions of the excavation depth

2.4.2 Probability of Activity above Pipeline

Only those third-party activities that are in the general vicinity of distribution pipelines have the potential to lead to TPD. P_A is the assumed probability of a given third-party activity being located above or adjacent to a distribution pipeline, in a way such that should the preventative measures fail with a sufficient digging depth, a pipeline would be hit. This probability is assumed based on the relatively low TPD rate of 2.3 hits per 1000 notifications (0.23%) for all utilities in Ontario [5]. It is assumed that 1% of all third party activities occur directly over distribution pipelines. The frequency of excavation activities that may lead to TPD (A_{TPD}) then equals the frequency of all excavation activities in a region ($A_{Activity}$) multiplied by P_A as follows:

$$A_{TDP} = P_A \bullet A_{Activity} \tag{2.8}$$

2.4.3 Failure of Preventative Measures

The Ontario Regional Common Ground Alliance (ORCGA) is an organization designed to reduce TPD through collaboration between utility companies, safety organizations, regulators, builders, and equipment suppliers by offering tools and public awareness of best practices regarding underground infrastructure. The DIRT report is a summary of data gathered by voluntary submission of underground utility third-party events submitted by the ORCGA industry stakeholders. Although the DIRT report contains data from a variety of underground utilities, a majority of reported incidents over the past three years have been submitted by the gas distribution pipeline operators [5]. Using available data from the ORCGA, Ontario OneCall, and access to utility damage prevention data, an analysis of common causes of preventative measure failure was conducted. Basic events that determine the failure of preventative measures were then assigned probabilities based on the survey data collected in Ref [1].

P_{FoC} is the probability of damage occurring due to failure to follow standard construction operating procedures associated with excavation around underground utilities. Common causes include but are not limited to

- failure to maintain clearance;
- failure to maintain marks;
- failure to use hand tools when required;
- improper backfilling, and
- failure to support exposed assets.

P_{FoC} is estimated to be 17%, the probability of failure of common practices in excavation using the common locate and mark method found in the survey data reported in Ref [1]. This method includes using a tool to locate the pipe and then marking the line using either flags or paint.

It is noted that Ontario OneCall requires five business days notice to submit a request. Therefore, it is inferred that the likelihood of a third party starting the excavation before the operator responds to the locate request is fairly low. Therefore, P_{DBL} is assumed to be 2% based on relevant survey data reported by Chen et al.[1].

In the city where digging depths were investigated incorrect markers were the primary cause of only one incident from 2014 to 2016. P_{IM} is determined to be 1% based on the survey data reported in [1]. This value was chosen based on the low frequency of reported damages due to incorrect markers.

P_{FAN} is determined using the survey data reported in [1], which indicates that the probability that a third party aware of a pipeline but neglecting to notify OneCall has approximately a 66% probability of avoiding the pipeline during the excavation. On the other hand, the probability of a third party unaware of a pipeline has a negligible probability of avoiding the pipeline during the excavation; therefore, P_{FAU} is assumed to equal one. It is further reported in [1] that 15% of the time they were unaware that there was a pipeline in the area (P_{UoP}). P_{NCL} is taken as 43% and is the average probability of P_{FAU} and P_{FAN} using Eq. (2.9):

$$P_{NCL} = ((1 - P_{UoP}) \bullet P_{FAN}) + (P_{UoP} \bullet P_{FAU}) \tag{2.9}$$

In cases where TPD events could be characterized as falling into multiple categories, such as both a failure of construction practices and incorrect markers, the event is placed into one root cause category to maintain independence between variables and to avoid double counting events. Based on the above discussions, the probabilities of basic events in the fault tree shown in Figure 2.2 are evaluated and summarized in Table 2.1 (see the last column).

Table 2.1 Fault Tree Model Events

Event	Name	Type	Probability
1	Probability of Hit (P_{Hit})	AND Gate	0.0029
2	Failure of Preventative Measures (P_{PF})	OR Gate	0.36
3	Locates Failure (P_{NL})	AND Gate	0.22
4	No Locates by Utility (P_{NLU})	OR Gate	0.50
5	No Call (P_{NC})	OR Gate	0.49
6	Digging Depth Exceeds Depth of Cover (P_{DEC})	Basic Event	0.80
7	Activity Near Pipeline (P_A)	Basic Event	0.01
8	Failure of Construction Practices (P_{FoC})	Basic Event	0.17
9	Incorrect Markers Placed (P_{IM})	Basic Event	0.01
10	No Locate by Contractor (P_{NLC})	Basic Event	0.43
11	Dig Before Locate is Completed (P_{DBL})	Basic Event	0.02
12	No Call Made, Neglect (P_{NCN})	Basic Event	0.33
13	No Call Made, Unaware (P_{NCU})	Basic Event	0.24

2.5 Model Validation

2.5.1 Defining Activity Rate

The rate per km of distribution pipeline per year of third-party excavation activities within a region, $A_{Activity}$, is determined indirectly using the locate data. It is noted that the activity rate should include both notified (i.e. through OneCall) and unnotified activities. The latter must be estimated indirectly due to a lack of data.

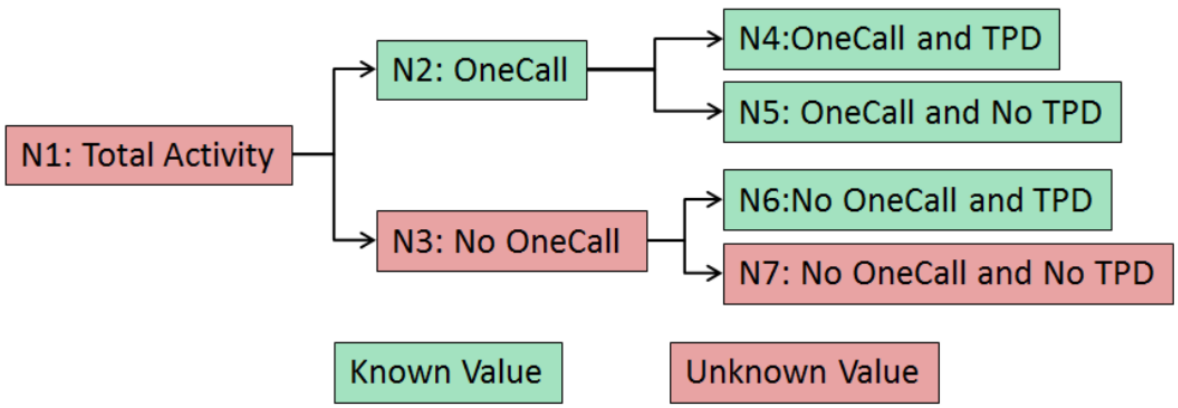

Figure 2.6 Possible Outcomes of Third-Party Activity

Figure 5 shows the possible outcomes of an excavation event. As shown in the figure, the number of activities that are not notified and do not lead to TPD is unknown. Chen et al. [5] suggested that $A_{Activity}$ be estimated from the frequency of notified activities, A_{Locate}, as follows:

$$A_{Activity} = \frac{A_{Locate}}{(1-P_{NCN})(1-P_{NCU})} \tag{2.10}$$

where P_{NCN} and P_{NCU} are the probabilities of a third-party neglecting to notify OneCall and unaware of OneCall, respectively, as listed in Table 1. Chen et al. reported from survey data that in 24% of excavation events third-parties are unaware of OneCall and in 33% of excavation events third-parties neglect to contact OneCall. Utility locate records and estimates of awareness from Ontario OneCall place the total probability of OneCall not being notified between 50-60%, which is line with Chen et al.'s findings. Based on these findings it is assumed that the probabilities from Ref [1] are valid assumptions for distribution pipelines. By substituting P_{NCN} = 0.33 and P_{NCU} = 0.24 into Eq. (2.10), $A_{Activity}$ = 1.96A_{Locate}.

2.5.2 Comparison of Predicted and Reported TPD

The proposed TPD model is validated using the 2017 locate data from three different cities (A, B and C) in Southwest Ontario. The predicted number of TPD (N_{TPD}) are compared with the recorded number of TPD in A, B and C, respectively, in Table 2. The predicted number of TPD is obtained by using the following equation:

$$N_{TPD} = P_{Hit} \bullet A_{Activity} \bullet \ell_{Dist\ Pipe} \tag{2.11}$$

where $\ell_{Dist\ Pipe}$ is the length (km) of distribution pipeline systems in a given city. Note that $A_{Activity}$ = 1.96A_{Locate} as explained in Section 5.1 with A_{Locate} being directly evaluated from the number of locate requests in each city. In 2017, there were 12719, 5049 and 7104 locate requests in A, B and C, respectively.

As shown in Table 2.2, the predicted number of TPD agree very well with the recorded number of damages for A, B and C in 2017. This suggests that the TPD model proposed in this study is a viable tool for the integrity management of distribution pipelines with respect to TPD.

Table 2.2 Model validation using 2017 damage records

City	Approx. Population (1000)	Pipe Length (km)	$A_{Activity}$ (km-year)	Predicted # of TPD	Recorded # of TPD
A	350	2615.4	9.55	71	71
B	350	2259.4	2.23	28	33
C	200	1199.7	10.96	40	41

2.6 Conclusions

In the present study, a TPD model is developed to quantify the probability of failure of the distribution pipeline due to third party excavation activities. The TPD model consists of an FTA model to estimate the probability of hit of a given distribution pipeline by third party excavation activities, but conservatively assumes that the pipeline will fail with certainty once hit by excavation activities given that distribution pipelines are typically small-diameter thin-walled pipes with very low puncture resistance. The distribution FTA model is developed using TPD and locate records from 2014-2016 and survey data from transmission FTA models. This model is then validated on the comparison of predicted and actual 2017 damage records of three municipalities in southwestern Ontario with populations varying from 200,000 to 350,000. The TPD model developed in this study can be a viable tool for the reliability- and risk-based integrity management of distribution pipelines with respect to TPD.

2.7 References

[1] Q. Chen and M. Nessim. "Reliability-based Prevention of Mechanical Damage to Pipelines." Technical Report No. L51816. C-FER Technologies, Edmonton, Canada.1999.

[2] Wei Liang, Jinqiu Hu, Laibin Zhang, Cunjie Guo, and Weipeng Lin. "Assessing and classifying risk of pipeline third-party interference based on fault tree and SOM." *Engineering Applications of Artificial Intelligence* Vol. 25 Issue 3 (2012): pp. 594-608. DOI 10.1016/j.engappai.2011.08.010. https://www.sciencedirect.com/science/article/abs/pii/S0952197611001539.

[3] Common Ground Alliance. "Damages Reported by State- All States 2016." DIRT 2016 - Interactive Report. http://commongroundalliance.com/dirt-2016-interactive-report

[4] Richard Durrer, Brandon Denton, and Jennifer Parent. "2016 DIRT Report Version 10.0." Ontario Regional Common Ground Alliance, Conconr, Canada. http://orcga.com/wp-content/uploads/2017/04/2016-report-final-update-without-marks.pdf.

[5] Common Ground Alliance. “Damages Reported by State- Ontario 2016.” DIRT 2016 - Interactive Report. http://commongroundalliance.com/dirt-2016-interactive-report

3 Risk Assessment of TPD on Natural Gas Distribution Pipelines Using Historical Data

3.1 Introduction

3.1.1 Significance of Quantitative Risk Assessment of TPD on Distribution Pipelines

Third-party damage (TPD) is a leading cause of failure for gas distribution systems [1]. An analysis of the US Pipeline and Hazardous Material Safety Administration (PHMSA) data since 1984 shows that TPD accounted for over 50% of incidents on distribution pipelines. Analyses of reported TPD in the continental United States and five Canadian provinces (Quebec, Ontario, Saskatchewan, Alberta, and British Columbia) in 2016 showed that there were over 91,000 reported incidents of TPD on distribution and service lines [2]. As the dominant cause of failure for distribution pipelines the ability to quantify the risk associated with TPD can help distribution pipeline operator prioritize maintenance planning and devote resources to improve public awareness of TPD.

3.1.2 Literature Review of Quantitative Risk Assessment on Distribution Pipelines

Pipelines are the safest method of transporting natural gas [3], though serious failures do occur and an accurate assessment of risk allows for a more informed assessment of the likelihood and consequence of these failures. The Alberta Energy Regulator (AER) uses a qualitative rating system in which incidents are ranked as low, medium, or high based on impacts to the public, wildlife, or environment [3]. The British Columbia Oil and gas Commission uses a similar approach ranking accidents on a scale of 1-3 with an additional category for minor incidents with no potential impacts to anyone but the permit holder.

On a national level, in Canada the National Energy Board (NEB) regulates only inter-province pipelines accounting for 9% of oil and gas pipelines in Canada. None of these regulated pipelines are distribution pipelines. In comparison the PHMSA regulates 76% of all pipelines in the United States and provides a substantial database of distribution incidents to the public. A National Research Council review recommends improving

Canadian data collection to better understand the impact of pipeline accidents [3], however the current lack of public Canadian data requires partnership with other stakeholders to gather the necessary information to provide meaningful quantitative analysis of TPD risk to Canadian distribution pipelines.

Distribution pipelines are usually only discussed when incidents occur [4] however, the economic damage from distribution pipeline in the United States was 70% higher than transmission pipelines between 2015-2018. There were also 123 deaths associated with distribution pipelines and 29 deaths associated with transmission pipelines during that period. Transmission pipeline research is not always directly applicable for use on distribution systems. Risk analysis on damage given a hit and the probability of delayed failure are important factors in the analysis on transmission pipelines [5] but, as shown in Chapter 2, the resistance to puncture of distribution pipelines can be assumed to be negligible. Transmission risk assessment research has also been completed using Bayesian modeling [6], but in addition to not all of the parameters being applicable to distribution pipelines these analyses often use software packages that are uncommon in industry, increasing the barriers to implementation. Analysis based on historical data requires a relatively large database of failure incidents [7]. Such data are difficult to obtain in Canada due to a lack of publicly available centralized pipeline incident database. To complete a distribution pipeline historical incident analysis, partnership with the utility operators responding to these incidents is required.

Risk management of natural gas pipelines is primarily accomplished using two methods, objective and perspective [8]. In the objective method a historical analysis of risk is completed to attempt to determine future risk, usually using the likelihood of an event occurring and the magnitude of the consequence. Perspective risk management uses a more subjective approach and often is based on the experience of experts to determine risk. Experimental modeling is also performed to determine the consequence of some risks related to pipelines, such as leaks [9], but it is often difficult to recreate TPD in this setting. In practice, the risk associated with the failure of natural gas distribution systems is generally evaluated qualitatively using the risk matrix approach [10]. This approach evaluates the risk as a numerical index. Typically this numerical index is created by a qualitative ranking of both the likelihood and severity of consequences as very low, low, moderate, high, or very high based on predetermined criteria, and then assigning a score (e.g. 1 through 5) for each of the likelihood and severity of consequences. Risk is then defined using Eq.3.1:

$$Risk = Likelihood \bullet Consequence \tag{3.1}$$

Using this definition of risk events can be categorized and ranked in order of priority. These risk index scores are typically grouped into four categories (i.e. Lowest, Moderate, High, and Highest). A representation of these categories is shown in Figure 3.1 below:

		Consequence				
		1	2	3	4	5
Likelihood	1	1	2	3	4	5
	2	2	4	6	8	10
	3	3	6	9	12	15
	4	4	6	12	16	20
	5	5	10	15	20	25

Risk	Score
Lowest	1-4
Moderate	5-10
High	11-16
Highest	17-25

Figure 3.1 Example Risk Index Matrix

These scores, if likelihood and consequence are expressed based on an analysis of previous events, can be used as a basis of risk assessment. However, there have been few studies on the consequences and likelihood of TPD-caused failures of distribution pipelines and using this matrix method in conjunction with additional indicators such as the cost and frequency of damages. By combining this existing method with an analysis of historical data a more quantitative method of risk assessment can be developed.

3.1.3 Objective and Scope

The objective of this study is to develop a risk assessment model for distribution pipelines regarding TPD. An approach to quantify the consequence of distribution pipeline failures due to TPD is developed and used in conjunction with the likelihood model developed in Chapter 2, which can be directly employed in the risk assessment. This assessment is then applied to the distribution pipeline network in London, Ontario as a case study.

3.2 Risk assessment approach

As a result of the relatively low probability of any specific section of pipe being damaged by TPD, it is advantageous to group portions of the distribution network into areas and assign risk based on the characteristics of the area, rather than each individual section of pipelines. As these networks are typically owned by a single stakeholder, areas can be adjusted to meet the needs of the organization. The method of area analysis is commonly used in pipeline analysis, such as the class location assessment using the population density surrounding the pipeline, to allow for a greater understanding of the risk to the community.

To define the risk associated with the failure of distribution pipelines due to TPD in an area (e.g. a city or municipality), the distribution pipeline network within the region is divided by sub-regions, and for each sub-region a risk value is evaluated for the distribution pipelines included in the region. The fault-tree model developed in Chapter 2 will be used to evaluate the likelihood of TPD failure for the pipelines in a sub-region, and the consequence model described in Section 3.3 is used to quantify the failure consequences due to TPD.

3.3 Quantification of Failure Consequences of Distribution Pipelines due to TPD

3.3.1 General approach

Based on the recommendations of experienced engineers and referencing the consequence matrix developed by Union Gas, various criteria are adopted as the basis for assessing consequences of failures of distribution pipelines as shown in Table 3.1.

Table 3.1 Consequence Criteria

Criteria	Consequence Severity				
	C1	**C2**	**C3**	**C4**	**C5**
Injury	Minor Injury (First Aid)	OSHA Recordable, Restricted work	Loss of time, hospitalization	Long Term Disability or Public Health Hazard	Fatality or large Public Health Hazard
Environmental	Low impact to land only	Moderate impact to land/air. Remediation done by onsite employees	Impact to land/air offsite. Remediation requires support.	Major impact to water course or ground water. Considerable cleanup required	Severe environmental impact. Local species destruction and long recovery period
Direct Monetary Impact	<$10,000	$10,000-99,999	$100,000-999,999	$1M-5M	>$5M
Number of Customers Impacted	<100 Customers	100-499 Customers	500-999 Customers	1000-5000 Customers	>5000 Customers

Table 3.1 allows for events containing a wide variety of circumstances to be grouped into similarly serious levels of impact. Assigning these levels also allows for a monetary value

to be estimated for consequences that are difficult to attribute finical estimates, such as environmental impact or injury. These definitions can be modified to suit organizational need, or new categories, such as public relations impact, could be added to increase the dimensions in which the risk level is classified.

A given distribution pipeline incident is assigned a single consequence severity index based on Table 3.1 and the sorting algorithm depicted in Fig. 3.2.

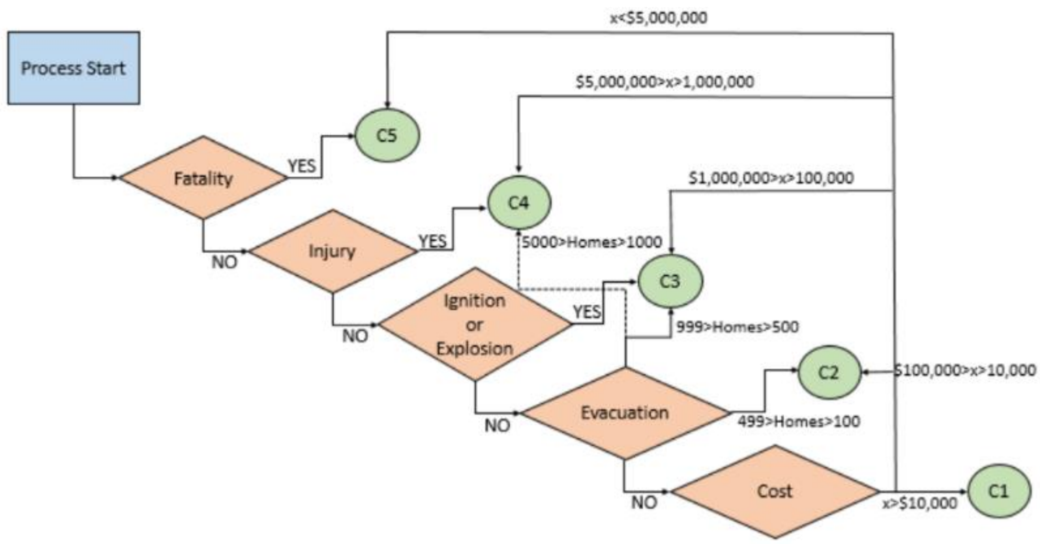

Figure 3.2 Consequence Level Sorting Process

In Fig. 3.2, *x* is the direct monetary cost and *Homes* is the number of customers impacted. This sorting algorithm allows for a determination of the highest consequence index based on the defined definitions in each case in Table 3.1. An example of this is a TPD event in which there is a fatality (C5) and the total cost is $120,000 (C3). Using this process the incident is sorted based on the C5 fatality classification before it is evaluated on a cost basis. This method includes the indirect costs (such as loss of life) of TPD to provide a more accurate overall impact.

As larger diameter pipelines usually feed lower diameter pipelines, it is assumed that the failure consequence is mainly correlated with the pipe diameter. To reduce the data sparsity, four diameter groups are created (Table 3.2). These categories were chosen based on the typical use of the Nominal Pipe Size (NPS) in each category. For reference

Table 3.3 relates NPS to actual outer diameter (OD). Pipes in category D1 (NPS2 and smaller) are typically used in services and streets off main branches of distribution line. D2 category pipes are mainly used to tie larger mains together and feed D1 pipes. D3 and D4 are typically found on major streets and feed from a regulating station [11]. The flow of gas typically flows from larger to smaller diameter pipelines is illustrated in the sample distribution main shown in Figure 3.3.

Table 3.2 Diameter Classification

Diameter Code	NPS
D1	NPS ≤ 2
D2	2 < NPS ≤ 6
D3	6 < NPS ≤ 12
D4	NPS > 12

Table 3.3 NPS to OD

NPS	OD (mm)
2	66.33
4	114.30
6	168.28
8	219.08
12	323.85

For each diameter group, as defined in Table 3.2, a single weighted average consequence severity index can be calculated from Eq. (3.2):

$$C_i = \sum_{j=1}^{m=5} P_{ij} \cdot j \tag{3.2}$$

where C_i is the weighted average consequence severity index for the ith (i = 1, 2, 3 or 4) diameter group, and P_{ij} is the percentage of distribution pipelines within the ith diameter group that are associated with the failure consequence severity index of j (j = 1, 2, …, 5). For all the distribution pipelines within a given area, a single weighted average consequence index, C_{Total}, is then evaluated as follows:

$$C_{Total} = \sum_{i=1}^{n=4} \frac{\ell_i}{\ell_{Total}} \cdot C_i \tag{3.3}$$

where ℓ_i is length (km) of distribution pipelines within the ith (i = 1, 2, 3 or 4) dimeter group, and C_{Total} is the total length (km) of the distribution pipelines within the area. For example, in Figure 3.3 a portion of a hypothetical distribution network is divided into the two areas with the yellow area (60% D1, 40% D2, 0% D3, 0% D4) and the purple area (30% D1, 30% D2, 15% D3, 25% D4) indicated by the colored shading. It is assumed that the same pipe length is included in the two areas:

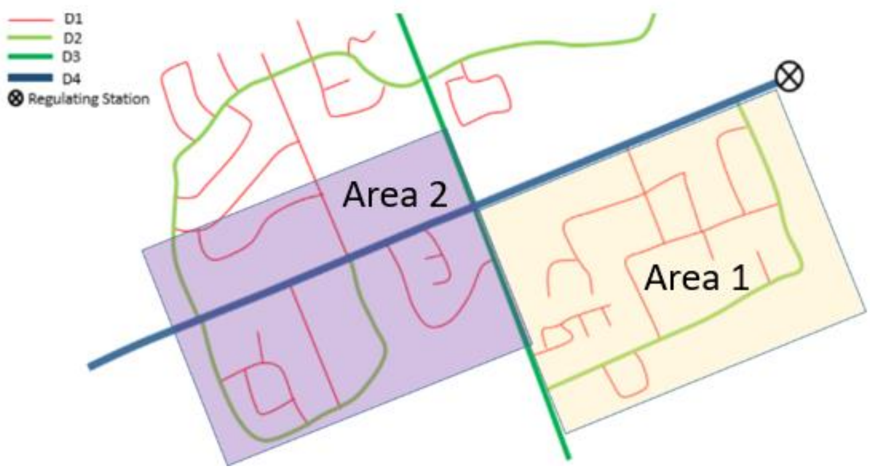

Figure 3.3 Sample Distribution Network with Area Polygons

Area two should be considered to be associated with higher failure consequences as it encompasses portions of the network that supply other customers downstream of the area (assuming gas flows away from the regulating station), providing it with the potential to affect significantly more customers. To aid in the comprehension of this evaluation an estimated cost was determined based on the financial consequence criteria in Table 3.1.

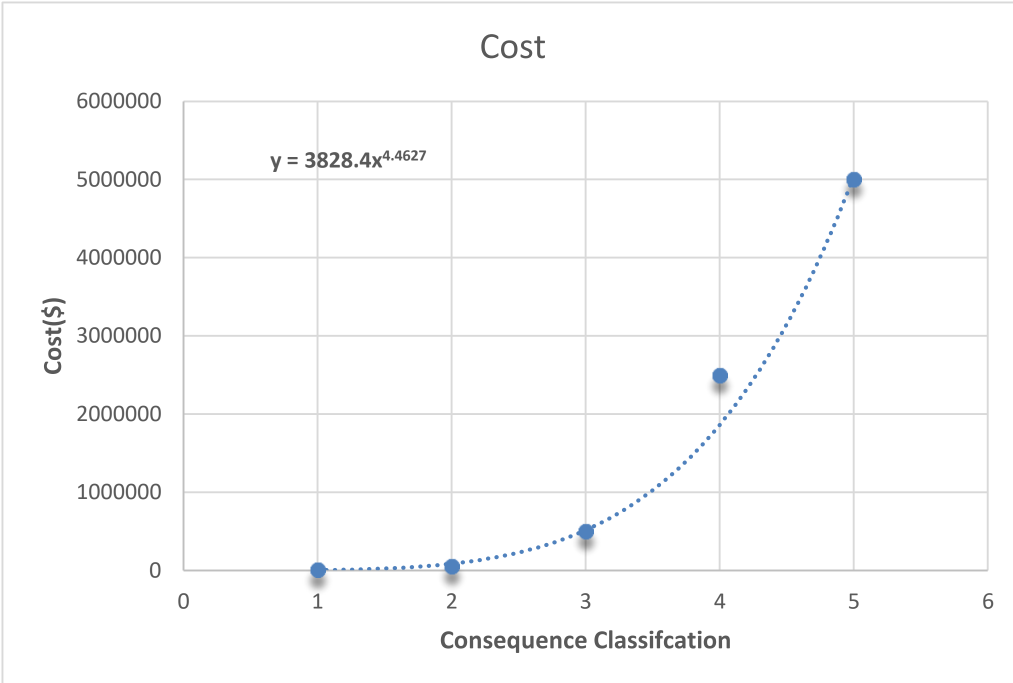

Figure 3.4 Consequence to Cost Translation

Figure 3.4 shows a fitted power-law curve using the midpoint values in C1 through C4 catogories of the Direct Monetary Impact criterion shown in Table 3.1 to assign a cost, i.e. C1 through C4 corresponding to $5,000, $50,000, $500,000, $2,500,000, respectively, and assigning a cost of$5,000,000 to C5. The cost associated with an incident is the highest consequence level as defined by the categories outlined in Table 3.1. For example, a TPD event in which there is a fatality (C5) and the total monetary cost is $120,000 (C3) the cost of this incident would be taken as that of a C5 incident with a cost of $5,000,000 to more accurately reflect the overall cost of an incident of this magnitude. Financial implications are assumed to be an important consideration in the evaluation of risk, as a result cost is considered a relevant index when assessing TPD on distribution systems. The total expected cost of failure of distribution pipelines, $Cost_{Total}$, in an area is calculated as follows:

$$Cost_{Total} = \sum_{i=1}^{n=4} Cost_i \cdot N_i \tag{3.4}$$

$$Cost_i = 3828.4 \cdot C_i^{4.46} \tag{3.5}$$

where $Cost_i$ is the cost of a failure of a distribution pipeline in the *ith* diameter group estimated using the power-law fitting equation shown in Fig. 3.4, and N_i is the expected number of TPD failures for the distribution pipelines in the *ith* diameter group within a given time period, e.g. one year, and can be evaluated using the fault tree model described in Chapter 2.

3.3.2 TPD Consequence Analysis Based on Historical Incident Data

3.3.2.1 Union Gas Data

The Union Gas incident data and PHMSA incident data are analyzed to investigate the relationship between the failure consequences and diameter. Union Gas's historical TPD failure incident records included 931 TPD-caused distribution incidents in Ontario over the period from 2014 to 2016 on approximately 65,000 km of distribution pipeline. A sample of distribution network is shown in Figure 3.5. By applying the approach described in Section 3.3.1, the consequence severity levels for the 931 Union Gas incidents are determined. The breakdown of the consequence severity level by the diameter group is shown in Table 3.4.:

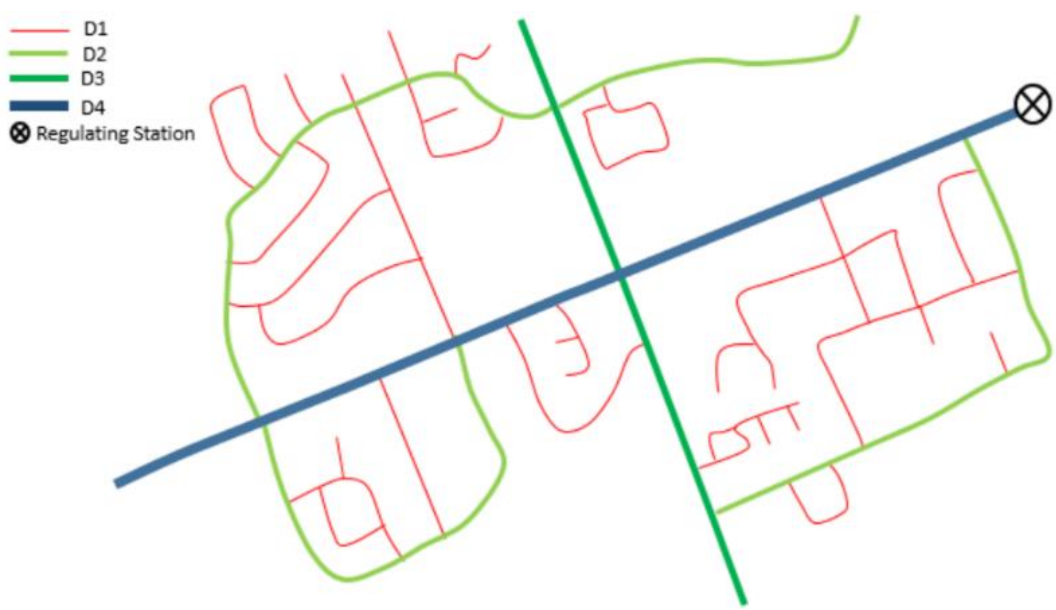

Figure 3.5 Sample Distribution Network

Table 3.4 Union Gas TPD Incident Breakdown by Diameter Group

		D			
		1	**2**	**3**	**4**
C	**1**	893	21	0	1
	2	4	1	0	0
	3	0	1	0	0
	4	0	0	0	0
	5	0	0	0	0

Of the Union Gas incidents, 897 of the 931 incidents occurred on D1 category pipes. This data lacks a significant sample of TPD on larger diameter pipes. To account for this, the Union Gas data was supplemented with additional records from the United States.

3.3.2.2 PHSMA Distribution Records

Due to the relatively low frequency of large diameter damage events in the Union Gas incident data, distribution records from PHMSA were analyzed from 2004-2016. In the United States the code of federal regulations (CFR) governs the report-ability of incidents involving natural gas release. 49 CFR § 171.16 requires:

"incidents to be reported through PHMSA within 30 days of the incident, and a follow-up written report within one year of the incident, based on certain circumstances, to be reported to PHMSA through the Hazardous Materials Incident Report Form DOT F 5800.1" [12]

The operators of these pipeline facilities report this data in accordance with Part 191 and Part 195 of PHMSA's pipeline safety regulations [12]. Information on these incidents is publicly available and provides detailed information on the causes and consequences of a variety of incidents, including TPD. The information within the period of collected data includes:

- Geographic information (street address, latitude, longitude)
- Gas release, ignition, and explosion
- Evacuation, injury, and fatality
- Pipe attributes (material, diameter, MOP)

- Root cause
- Third party practices followed (markers, notification, accurate information provided)

The PHMSA database (https://www.phmsa.dot.gov/data-and-statistics/pipeline/distribution-transmission-gathering-lng-and-liquid-accident-and-incident-data) contains all reported records on damage caused to distribution natural gas pipelines that resulted in greater than US$50,000 of damage in the United States [13]. After removing non-TPD incidents there were 503 recorded incidents from approximately 1.2 million km of distribution pipe over the period of 2004-2016. Based on this information, TPD events were classified into different consequence values (Table 3.5) using the same sorting process described for the Union Gas data as shown in Fig. 3.2.

Table 3.5 PHMSA TPD Incident Consequences Breakdown by Diameter Group

		D			
		1	**2**	**3**	**4**
C	**1**	0	0	0	0
	2	87	98	60	6
	3	64	34	9	5
	4	96	20	2	1
	5	19	2	0	0

The minimum reporting dollar value of $50,000 USD in this database results in only events of C2 and greater (as the C1 maximum is $10,000), however smaller consequence incidents are captured in the utility data obtained through Union Gas distribution records. Combining these two sources of information provides a sample of the consequence of a TPD incident. The PHSMA data was included to capture the projected consequence of the less frequent but often more impactful damage on larger pipelines. Including regionally specific data only, the lack of examples of these incidents would underestimate the potential consequence associated with larger diameter pipelines. After characterizing the available TPD incidents by consequence and dimeter, they are combined with the Union Gas records for a total of 1424 incidents:

Table 3.6 Combined TPD Event Breakdown by Diameter

		D			
		1	**2**	**3**	**4**
C	**1**	893	21	0	1
	2	91	99	60	6
	3	64	35	9	5
	4	96	20	2	1
	5	19	2	0	0

Using this data the distribution of consequence indices for each diameter group can be developed as shown in Fig. 3.6. The average consequence index for a given diameter group can then be evaluated using Eq. (3.2).

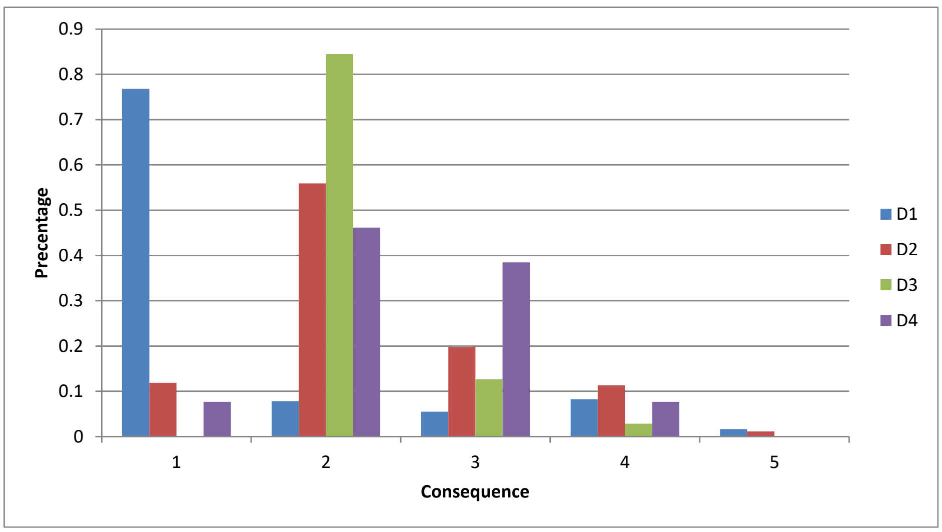

Figure 3.6 Consequence Probability by Diameter

3.4 Quantification of Failure Likelihood of Distribution Pipelines due to TPD

Based on the Union Gas's practice, a likelihood index (Table 3.7) is assigned to the distribution pipelines in a given area based on the probability of failure (i.e. hit) for a given excavation activity. Note that the probability of failure is evaluated using the fault tree model described in Chapter 2.

Table 3.7 Likelihood Criteria

Criteria	L1	L2	L3	L4	L5
Qualitative Evaluation	Remote, remote chance of happening	Rare, may occur during facility lifetime	Occasional, expected to occur once during lifetime	Likely, expected to occur several times during lifetime	Almost Certain, expected to occur several times during lifetime
Probability	P < 0.0001	0.0001-.001	.001-.01	.01-.5	0.5-1

Based on the results of Chapter 2, the probability of failure given an activity is the same for pipelines in different diameter groups, but the frequency of TPD incidents within a time period (e.g. one year) is dependent on the rate of activity and the length of pipelines in the area (Eq. 3.6). As a result, the risk indices for different areas, determined from the risk matrix approach, vary due only to the variations of the consequence indices in different areas. The risk index is most often used in the industry to classify the risk of a single incident or to evaluate the relative risk of various situations, which is reflected by the constant likelihood and is more focused on the impact of an incident in reference to the currently used risk index. By evaluating the areas using the risk index, frequency of TPD incidents, and total expected cost in an area, the traditional risk matrix is enhanced to provide a more comprehensive evaluation of the risk due to TPD in each area.

3.5 Risk Assessment Case Study

3.5.1 Defining Area Polygons

The city of London, Ontario, Canada is used as a case study for the risk assessment approach described above. London is a city with a population of approximately 380,000 and is sub-divided into 14 municipal wards (Fig. 3.7) [14]. These boundaries are generally defined by major planning features, such as roads, or physical boundaries, such as the Thames River, as these features also play a role in the design of distribution systems and contain similar populations they are a convenient method of dividing the city for analysis.

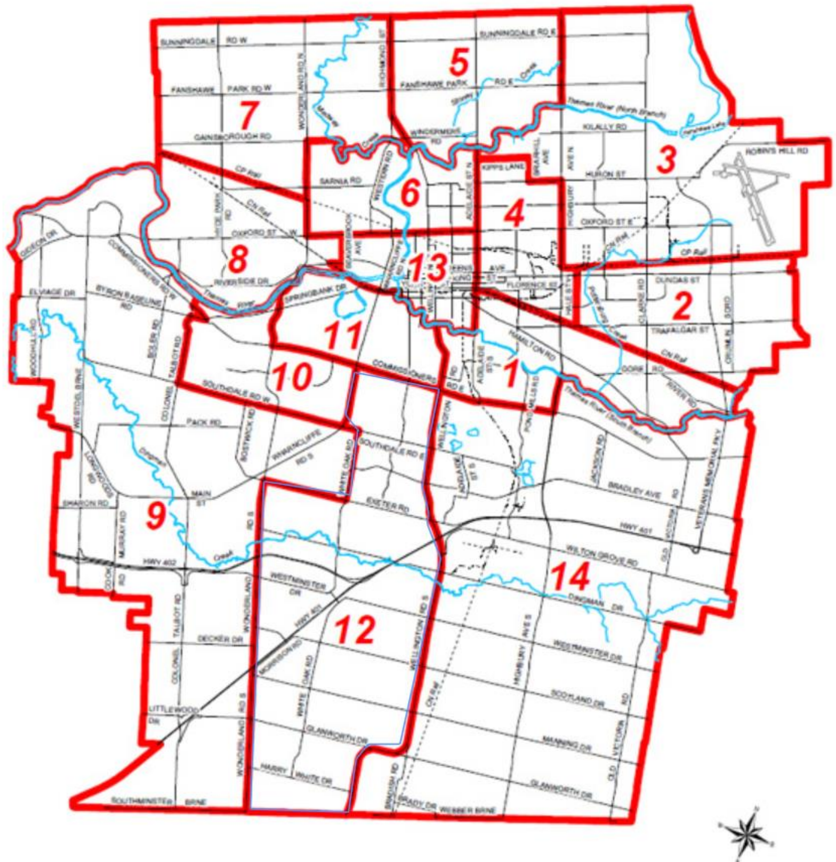

Figure 3.7 Ward Map of London, ON[14]

London has 2,717 km of distribution piping within the city boundaries. The lengths and diameters of the distribution pipeline system in London was determined using GIS mapping exports. GIS models are standard operating practice by most gas utilities. Using this information in combination with the spatial activity information the expected frequency and consequence of TPD can be identified for each municipal ward. The breakdown of the distribution pipeline length by ward and the diameter group is shown in Figure 3.8

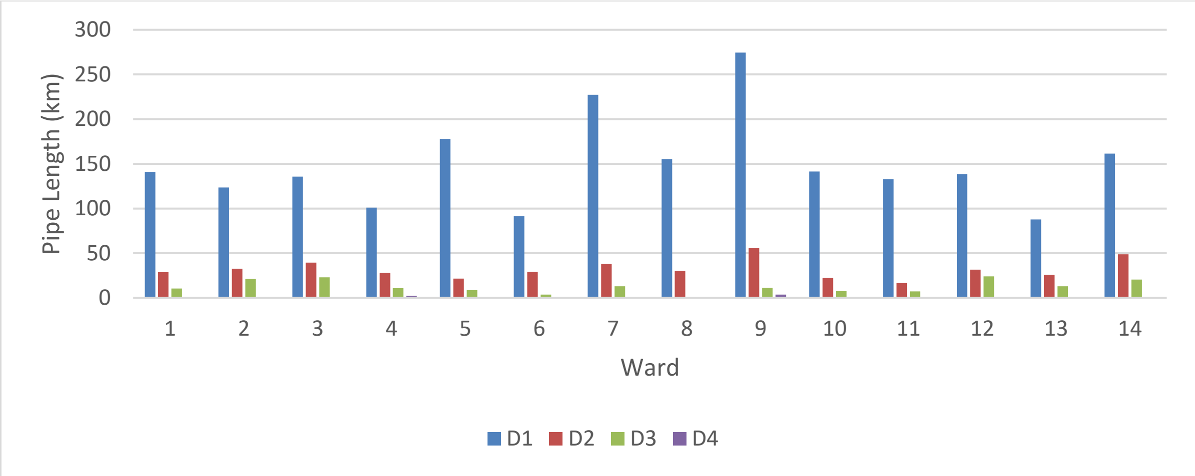

Figure 3.8 Distribution Pipe by Ward

3.5.2 Area Likelihood and Consequence Data Collection

The fault tree model described in Chapter 2 predicts that the probability of failure of the distribution pipeline given an activity is 0.0029, which corresponds to a likelihood index of L3 for all wards. To determine the frequency of TPD incidents in each ward, a spatial distribution of the locate requests within the city is required. Using Ontario OneCall ticket data for 2014-2016 the submitted street information was geocoded to assign a latitude and longitude. This data is used in the locate process and therefore should be available in most jurisdictions. For this period 20,640 tickets were geocoded (Fig. 3.9), providing an estimate of the spatial distribution of activities in London

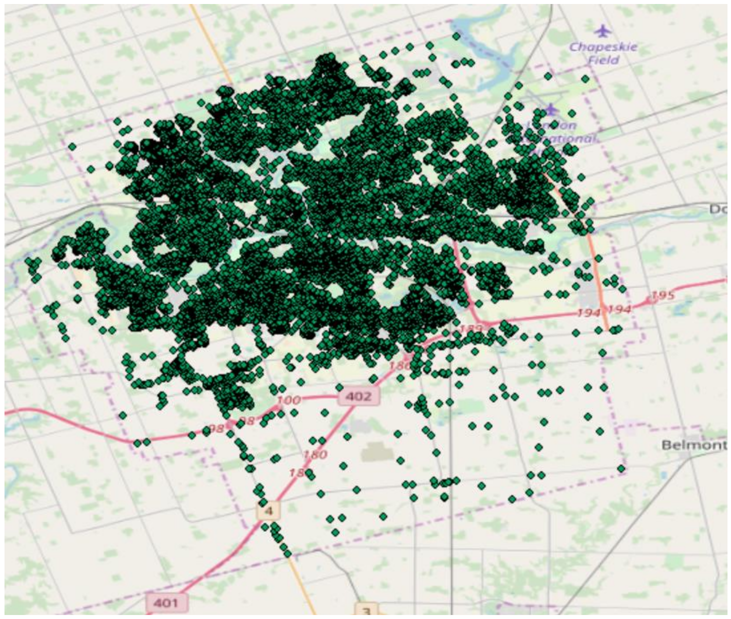

Figure 3.9 Spatial Distribution of Locate Tickets in London, ON

Overlaying these locations with the ward boundaries the frequency of activity in each ward (i.e. polygon) can be determined. Figure 3.10 shows the spatial distribution of locate requests overlaid onto ward polygons in ArcGIS, and Figure 3.11 shows the distribution of submitted locate requests by ward.

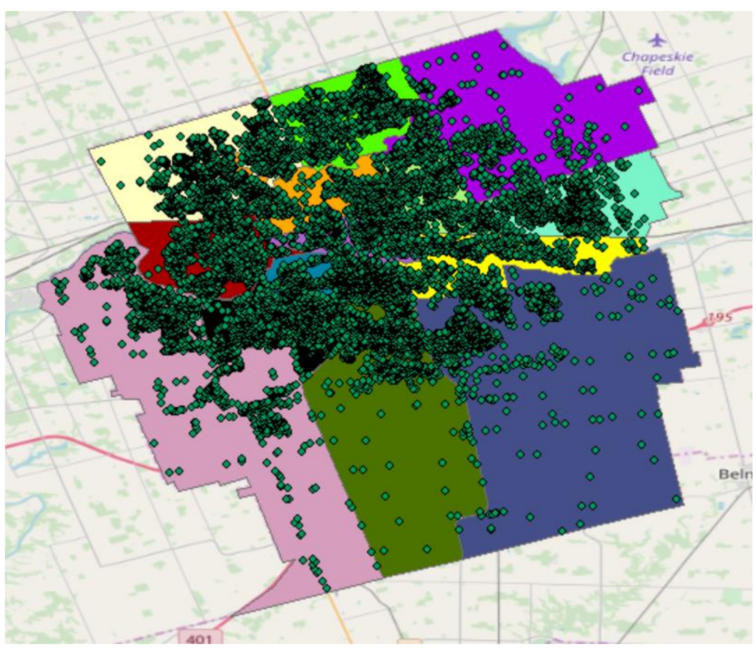

Figure 3.10 Spatial Distribution of Locate Requests with Ward Polygons

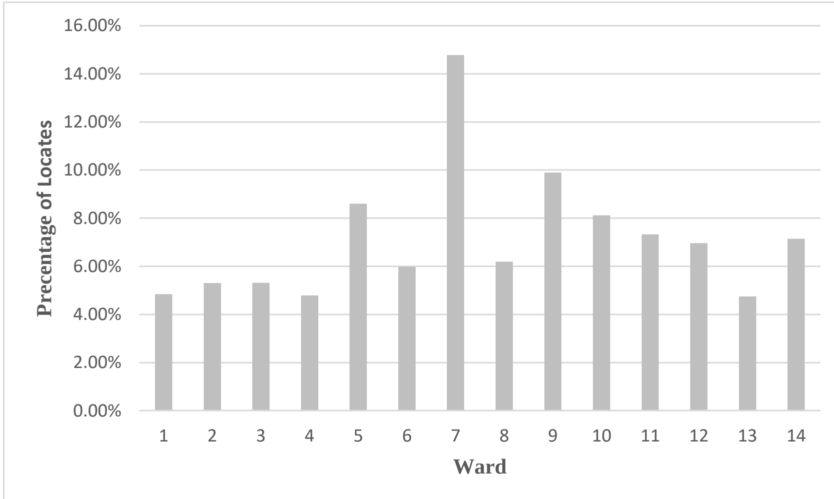

Figure 3.11 Distribution of Submitted Locate Requests by Ward

3.5.3 Area TPD Frequency Classification

The expected number of TPD incidents per year, N_{TPD}, in a given ward is evaluated using Eq. 3.6

$$N_{TPD} = P_{Hit} \cdot A_{Activity} \cdot \ell_{Total} \tag{3.6}$$

where P_{Hit} is the probability of failure (i.e. 0.0029) given an activity as determined by the fault tree analysis; ℓ_{Total} is the length (in km) of distribution pipeline systems in the ward, and $A_{Activity}$ is the number of activities per km-year in the ward, which equals $1.96A_{Locate}$ as explained in Chapter 2 with A_{Locate} being directly evaluated from the number of locate requests in the ward. A greater frequency of incidents requires a distribution company to respond more often, could possibly affect public perception, and indicates some combination of greater length or activity (as the probability of a hit remains constant), as a result frequency is considered a relevant consideration when assessing TPD on distribution systems.

3.5.4 Analysis and Results

Based on the approach described in the previous section, the evaluated risk indices based on the risk matrix approach, expected total cost and expected TPD frequency per year for all the wards are evaluated and summarized in Table 3.8.

Table 3.8 Indices by Ward

Ward	Area Properties				Consequence, likelihood, cost and risk				
	Distribution of Locate Requests	Length of Pipe(km)	Locates	Predicted Total Activity	C	L	Risk	N_{TPD} (# per year)	Cost
1	4.84%	180.19	616	1208	1.67	3	5.01	3.50	$132,226
2	5.31%	177.14	675	1323	1.73	3	5.19	3.84	$169,504
3	5.32%	198.09	676	1325	1.75	3	5.25	3.84	$178,752
4	4.79%	141.76	609	1193	1.73	3	5.19	3.46	$152,925
5	8.60%	208.2	1094	2145	1.62	3	4.86	6.22	$205,017
6	5.97%	124.03	760	1489	1.72	3	5.16	4.32	$186,011
7	14.78%	278.18	1880	3685	1.64	3	4.92	10.69	$372,078
8	6.19%	185.61	787	1543	1.64	3	4.92	4.47	$155,765
9	9.90%	345.09	1259	2468	1.67	3	5.01	7.16	$270,144
10	8.12%	171.23	1033	2025	1.64	3	4.92	5.87	$204,472
11	7.33%	156.4	933	1828	1.62	3	4.86	5.30	$174,739
12	6.96%	194.38	885	1735	1.72	3	5.16	5.03	$216,660
13	4.74%	126.23	603	1182	1.75	3	5.25	3.43	$159,507
14	7.14%	230.66	909	1781	1.74	3	5.22	5.16	$234,173

To aid in the interpretation these results the ArcGIS polygons of the areas can be used to create heat maps of the various indicator categories in Table 3.8. These maps can be used to show both the relative risk between the evaluated areas and the absolute risk in frequency and cost.

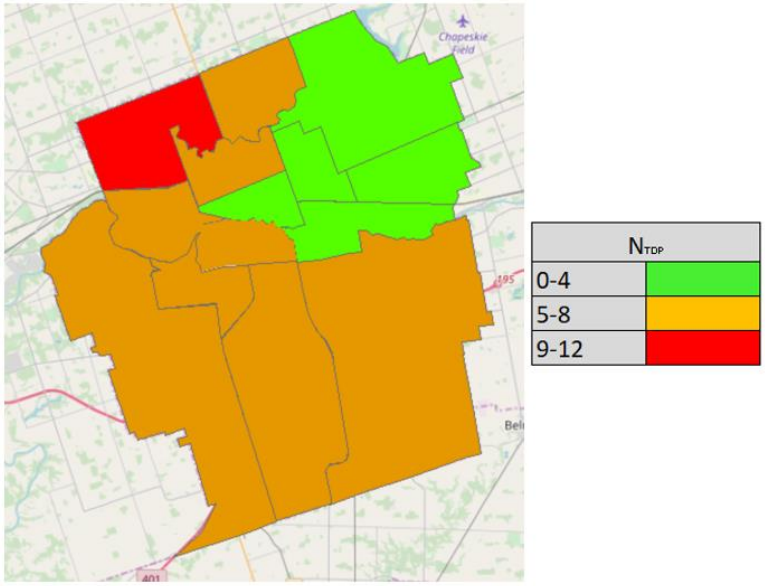

Figure 3.12 TPD Event Frequency (Total)

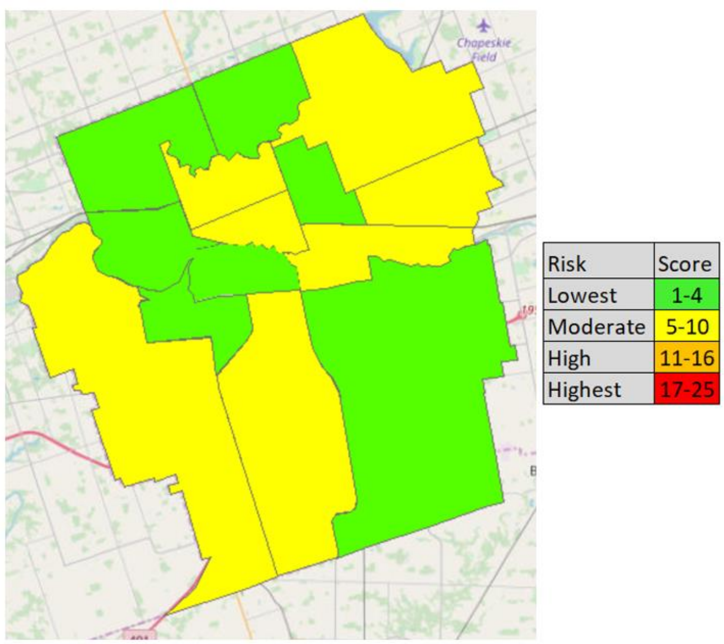

Figure 3.13 Risk Matrix Index Score

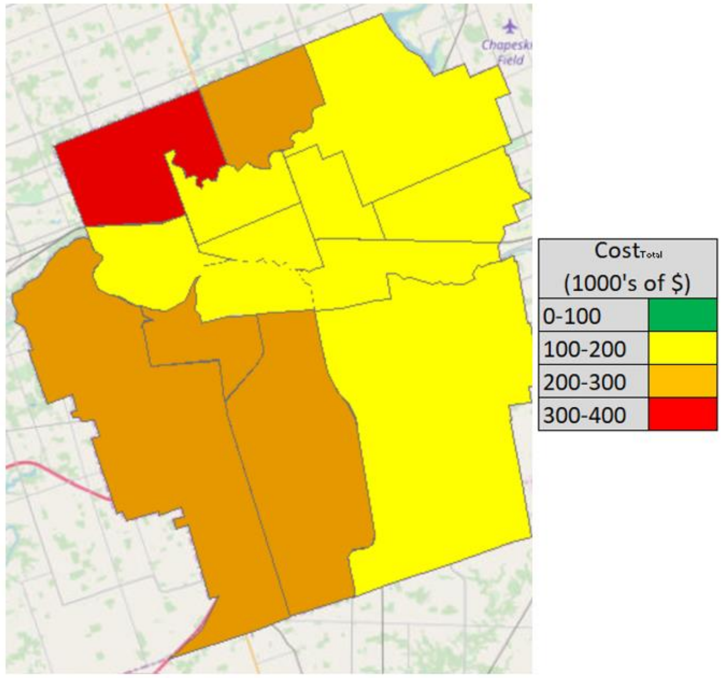

Figure 3.14 Total Area Cost

Figures 3.12-3.14 allow decision makers to visualize the areas within the city that would most benefit from TPD prevention resources; however, the relative weight of each of the three indicators (i.e. risk index, expected total cost per year and expected TPD frequency per year) can impact the final decision. For example, one decision maker may use the expected total cost per year as the only decision criterion (Figure 3.14), while another may use the risk index as the only decision criterion (Figure 3.13). The two decision makers may come to different conclusions. The compromise programing [15], as implemented in the COMPRO software package, uses an operational definition such as Eq. (3.7) to identify the wards that would most benefit from additional resources:

$$L_{p_j} = [\sum_{i=1}^{r=3} \alpha_i^P \left(\frac{z_i^* - z_{ij}}{z_i^* - z_i^{**}}\right)^p]^{1/p} \tag{3.7}$$

$$z_i^* = \max_j\{z_{ij}\} \tag{3.8}$$

$$z_i^{**} = \min_j\{z_{ij}\} \tag{3.9}$$

Eq. 3.7 calculates the distance in the indicator space (i.e. the risk index, expected cost and expected TPD frequency) between a given ward and a reference point, i.e. a hypothetical ward with the highest value for each of the three indicators. In Eq. (3.6), L_p is the distance between ward j (j = 1, 2, …, 14) and the reference point; α_i is the relative weight assigned to criterion i (i = 1, 2, 3) with $\alpha_1 + \alpha_2 + \alpha_3 = 1$, and p is a value a value greater than or equal to unity, and in this study is assumed to equal 2 [13]. The ward with the minimum value of L_p among all the wards is then considered the ward with the highest priority for resource allocations corresponding to the relative weight (i.e. α_i) assigned to each decision criterion. By varying the values of α_i, different scenarios in terms of the relative importance of different decision criteria can be further considered.

A compromise solution evaluation was completed using a variety of weights for each criteria as summarized in Table 3.9:

Table 3.9 Normalized Ranking of Compromise Criteria

Weighting Scenario	Weighting factor		
	# of TPD	Risk	Cost
1	0.333	0.333	0.333
2	0.417	0.167	0.417
3	0.200	0.600	0.200
4	0.600	0.200	0.200
5	0.200	0.200	0.600
6	0.167	0.417	0.417
7	0.417	0.417	0.167

These rankings simulate a variety of interest groups placing various levels of importance on the individual indices. Using this method the ranking of ward priority in each weight is shown in Table 3.10:

Table 3.10 Compromise Programing Priory Ranking

Ward	Weighting Scenario						
	1	**2**	**3**	**4**	**5**	**6**	**7**
1	14	14	11	14	14	12	13
2	7	10	4	11	9	7	7
3	6	9	3	10	8	5	6
4	10	13	7	13	12	9	9
5	11	4	13	3	6	11	11
6	5	8	5	8	7	6	5
7	1	1	9	1	1	4	2
8	13	11	12	9	13	13	12
9	2	2	8	2	2	3	4
10	8	5	10	4	5	10	10
11	12	7	14	7	10	14	14
12	4	6	2	6	4	2	3
13	9	12	6	12	11	8	8
14	3	3	1	5	3	1	1

Using this method allows for risk-based integrity management that provides a robust quantitative justification for the distribution of preventative measures using available data and simulating the needs of various stakeholders. Recommendations can now be made based on the results in the rankings.

Based on the compromise solution method of evaluation, it is recommended that Wards 7, 14, 9, and 12 receive priorities in terms of the allocation of damage prevention resource as they are consistently ranked as the highest priority within the various rankings. Referencing the ward map in Figure 3.8 these wards comprise the south and west boundaries of the city, suggesting that focusing resources on the outer, less developed regions of the city would be more efficient than the city center areas (Wards 4, 6, 11, and 13) for this particular community. In future work expanding the scope of the study to encompass a variety of municipalities could verify if this trend extends to other municipalities and would allow a more general set of recommendations to be made.

3.6 Conclusions

In the present study, a risk-matrix model for TPD of gas distribution pipelines is developed to allow for a more robust decision making process and better prioritization of the allocation of resources for operators of natural gas distribution pipelines. The model consists of a consequence classification procedure to estimate the severity of TPD events within an area based on an analysis of previous TPD events and combined with a previously developed likelihood model. Methods of collecting and classifying data from sources available to distribution companies are used to allow this procedure to be replicated in an industry setting.

This method is applied to estimate the TPD-posed risk to the gas distribution pipeline systems in London, Ontario, as a case study. Based on this case study a compromise solution method of evaluation is used to suggest areas where focusing damage prevention resource would be most effective. The wards which consistently ranked highly on this analysis comprised the south and west boundaries of the city, suggesting that focusing resources on the outer, less developed regions of the city would be more efficient than the city center areas for this particular community. The risk assessment approach developed in this study can be a viable tool for the risk-based integrity management of distribution pipelines with respect to TPD and other failure threats such as corrosion.

3.7 References

[1] Common Ground Alliance. “Damages Reported by State- All States 2016.” DIRT 2016 - Interactive Report. http://commongroundalliance.com/dirt-2016-interactive-report

[2] Common Ground Alliance. “Damages Reported by State- Ontario 2016.” DIRT 2016 - Interactive Report. http://commongroundalliance.com/dirt-2016-interactive-report

[3] C. Belvederesi, M.S. Thompson, and P.E. Komers.” Canada’s federal database is inadequate for the assessment of environmental consequences of oil and gas pipeline failures.” MSES Inc. Management and Solutions in Environmental Science, 207 Edgebrook Close NW, Calgary, AB T3A 4W5 Canada.

[4] Scott R and Scott A. “Assessing Grants to States for Oil and Gas Distribution Pipeline Safety Program Enhancement.” Energy Policy Volume 124, January 2019, Pages 332-345. https://doi.org/10.1016/j.enpol.2018.10.007

[5] Ma J et al. “Risk-Based Mitigation of Mechanical Damage.” 2016 11th International Pipeline Conference, Volume 1: Pipelines and Facilities Integrity. doi:10.1115/IPC2016-64040

[6] Guo X et al. “Risk identification of third-party damage on oil and gas pipelines through the Bayesian network.” Journal of Loss Prevention in the Process Industries Volume 54, July 2018, Pages 163-178. https://doi.org/10.1016/j.jlp.2018.03.012

[7] Lam C and Zhou W. “Statistical analyses of incidents on onshore gas transmission pipelines based on PHMSA database.” International Journal of Pressure Vessels and Piping 145 (2016) 29-40. https://doi.org/10.1016/j.ijpvp.2016.06.003

[8] Brogan, M. J. Evaluating risk and natural gas pipeline safety. Politics & Policy, 45(4), 657-680. doi:10.1111/polp.12211

[9] Bonnaud C et al. “Experimental study and modelling of the consequences of small leaks on buried transmission gas pipeline.” Journal of Loss Prevention in the Process Industries. https://doi.org/10.1016/j.jlp.2018.06.010

[10] J Agrawal and S Srivastava. “Methodology of Risk Management in Pipeline Projects.” 2013 India Oil and Gas Pipeline Conference IOGPC2013-9841, ASME, 2013.

[11] Mike Musial, Glenn DeWolf, Doug Orr, Julie Martin, and Pilar Odland. “Safety Performance and Integrity of the Natural Gas Distribution Infrastructure.” URS Corporation, Chicago, IL. 2005.

[12] United States of America Federal Regulation 49 CFR 171.16 - Detailed hazardous materials incident reports. 2004.

[13] United States of America Federal Regulation 49 CFR Part 191—Transportation Of Natural And Other Gas By Pipeline; Annual Reports, Incident Reports, And Safety-Related Condition Reports. 2004.

[14] City of London. “Electoral Ward Map”.https://www.london.ca/city-hall/city-council/pages/electoral-ward-map.aspx

[15] Simonović, S. Managing Water Resources. UNESCO, Paris, pp.550-560, ISBN 978-92-3-104078-8. 2009.

4 Conclusions and Recommendations

4.1 Summary

The main goal of this thesis is to develop a quantitative risk model of TPD to allow for a more robust decision making process and better prioritization of the allocation of resources for operators of natural gas distribution pipelines. The model consists of a FTA model, outlined in Chapter 2, developed based on previous studies of transmission pipelines to estimate the probability of hit of a given distribution pipeline by third party excavation activities, but conservatively assumes that the pipeline will fail with certainty once hit by excavation activities given that distribution pipelines are typically small-diameter thin-walled pipes with very low puncture resistance. The distribution FTA model is developed using TPD and locate records from 2014-2016 and survey data from transmission FTA models. This model is then validated on the comparison of predicted and actual 2017 damage records of three municipalities in southwestern Ontario with populations varying from 200,000 to 350,000.

In Chapter 3, a consequence classification procedure to estimate the severity of TPD events within an area based on an analysis of previous TPD events is combined with the previously developed likelihood model. This method is tested to demonstrate the practicality of implementation in a case study of London, Ontario and recommends techniques for data collection and decision analysis. The TPD model developed in this study can be a viable tool for the reliability- and risk-based integrity management of distribution pipelines with respect to TPD.

4.2 Conclusions

The following conclusions have been reached with regard to the quantification of risk of TPD on natural gas distribution pipelines:

1. The frequency of TPD events on a distribution system can be estimated using a fault-tree analysis method.

2. Distribution pipelines have a relatively low resistance to puncture, and a TPD frequency model assuming resistance to be zero is a valid approach.
3. Natural gas distribution companies have sufficient data available to use a quantitative risk approach to assess TPD risk, but much of that information is unavailable to researchers due to Canadian reporting policies.
4. The consequence of a TPD event can be estimated based on the pipeline attributes within that area.

The methodology described in this thesis is intended to be easily adaptable to other regions and the required data to carry out an analysis of this type should be available to most utility companies. Likelihood and consequence definitions can be modified to suit an organizations needs and definitions of risk. Additionally, the historical approach of defining consequence probabilities can be readily modified for a variety of utility types. This technique has the potential to be used as a basis for additional studies within natural gas distribution planning, as well as expanding its implementation to other sectors such as water, telecommunications, and electricity distribution.

4.3 Recommendations

Based on presented studies the several recommendations will be presented to improve the scope of knowledge regarding TPD on distribution pipelines:

1. Improving data regarding the amount of activity occurring over distribution pipelines. As discussed in Chapter 2 only those third-party activities that are in the general vicinity of distribution pipelines have the potential to lead to TPD. In this study an assumed probability was stated that a given third-party activity is located above or adjacent to a distribution pipeline, in a way such that should the preventative measures fail with a sufficient digging depth, a pipeline would be hit. A study to better determine this probability would increase the confidence of the fault tree approach.

2. Increase in publicly available data from Canadian sources. In Canada the National Energy Board (NEB) regulates only inter-province pipelines accounting for 9% of oil

and gas pipelines in Canada. None of these regulated pipelines are distribution pipelines. In comparison in the United States PHMSA regulates 76% of all pipelines and provides a substantial database of distribution incidents to the public. If Canadian authorities provided a similar level of public data to what is available from United States sources, more geographically specific recommendations and analysis could be completed by researchers.

3. Based on this case study the case study in Chapter 3, the compromise solution method of evaluation recommends that Wards 7, 9, 12, and 14 are worth focusing damage prevention resource as they are consistently ranked as the highest priority within the various rankings. These wards comprise the south and west boundaries of the city, suggesting that focusing resources on the outer, less developed regions of the city would be more efficient than the city center areas for this particular community. In future work expanding the scope of the study to encompass a variety of municipalities could verify if this trend extends to other municipalities and would allow a more general set of recommendations to be made.

4. As shown in Chapter 3, utility companies have sufficient records to use these modeling techniques, however they are contained in a variety of independent databases. If this information is integrated into the GIS platform, then analysis of TPD risk could be evaluated faster.

5. Working with other types of utility providers, such as water, electricity, and telecommunications companies could prove these modeling techniques effective across all utility distribution types, not exclusively Natural Gas.

Appendices

Appendix 2A: Justification for Common Transmission Base Events

Possible Events	Included or Excluded	Justification
Excavation on pipeline alignment	Included	Must be on alignment for possibility of damage
Third-party unaware of OneCall	Included	OneCall is responsible for both transmission and distribution tickets
ROW signs not recognized	Excluded	ROW signage not typically on distribution systems
No permanent markers	Excluded	Permanent markers not typically on distribution systems
Third-party chooses not to notify	Included	Same notification system (OneCall) for both transmission and distribution systems
Third-party fails to avoid alignment	Included	Similar for both transmission and distribution systems
No patrol during activity	Excluded	Distribution pipelines are not patrolled
Activity not reported by other employees	Excluded	Encompassed in no call probabilities
Excavation prior to operators response	Included	Same process for all pipelines
Temporary markers incorrect	Included	Same locate tools for both transmission and distribution systems

Accidently hitting marked pipeline	Included	Accidents happen to all utility types
Excavation depth exceeds depth of cover	Included	Must happen for any utility to have the possibility of damage
Law Factors	Excluded	Negligible impact in consideration of distribution pipelines
Public Relations	Excluded	Negligible impact in consideration of distribution pipelines
Natural Conditions	Excluded	Minimum depth of cover specifications include soil type considerations
Alarm Systems	Excluded	Notification of damage by mercaptan smell. No preventative alarms.

Curriculum Vitae

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